NEWSLETTER ABOUT NON-HYDROSTATIC DYNAMICAL CORE IN ARPEGE/IFS/AROME: JULY 2013.

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- We provide news about NH dynamical core in ARPEGE/IFS and AROME since 2008;
- Contributions for next releases of this NewsLetter are welcome;
- The diffusion is essentially internal (not institutional);
- Consequently, the tune is free (positive and negative statements are welcome, respecting a good balance).

1 Global models with finite difference vertical discretisation.

Tests done in 2008 have proven that we were able to run IFS (TL798L91) and ARPEGE (TL538c2.4L60), with the same timestep as with the hydrostatic model, provided a predictor-corrector scheme is switched on. Additionally Nils Wedi (ECMWF) did additional tests on idealised cases and small planet. Simulations without predictor-corrector scheme were not always stable, and consequently, were not deeply investigated.

Late 2012, Sylvie Malardel (ECMWF) came back to the NH model, now focusing on simulations without predictor-corrector scheme, because the predictor-corrector has some undesired significant overcost in IFS (more than the overcost in ARPEGE/AROME). She identified two issues:

- An instability above Himalayas.
- A 2-Dt type instability, linked to the "SETTLS" (stable extrapolating two-time levels scheme) treatment of the momentum equation RHS. This instability is not present in the hydrostatic model. This instability increases when increasing the timestep and leads to mass loss, especially near poles. Operational version of AROME uses the same formulation (SETTLS without predictor-corrector scheme), but the timestep is probably too small to generate this instability and mass loss.

Some instability above Himalayas was already noticed in 2007, but combining the use of a predictor-corrector scheme and of a lower value for `SIPR` (reference pressure for the semi-implicit scheme) was enough to remove it. However, without the predictor-corrector scheme, use of a lower value for `SIPR` is not sufficient to remove instability. The design of η coordinate may also act on this type of instability, especially if the coordinate goes too rapidly from pure σ-levels (near surface) to pure pressure levels (near top). When this occurs, some model layers appears to be very thin above mountains, with a detrimental effect on stability. For a set of pure σ levels (in which the role of `SIPR` totally disappears), the instability is not totally removed, but significantly reduced. It has been found that, both in METEO-FRANCE L70 set of levels and in ECMWF L91 set of levels, spacing above mountains goes too rapidly from pure σ-levels to pure pressure levels. It is planed to use a more regular vertical variation in the L105 set of levels targeted for future operations at METEO-FRANCE. In summary, though progresses were achieved, this problem is not completely solved.

About 2-Dt type instability, Sylvie Malardel made several tests:

- Instability does not occur if a non-extrapolating scheme ("NESC") is used in the RHS of momentum equation (still without predictor-corrector); but such formulation is less accurate.
- An idea combining a "SETTLS" scheme for the hydrostatic part of the RHS, and a "NESC" scheme for the NH anomaly was considered. But it was found that it was not convenient to write something like this in the code. No working formulation has been found concretely from this path.
- Using second-order uncentering (`XIDT` > 0) reduces this instability.
- To reduce this instability, it seems that some "friction" could be added to some terms in the RHS of momentum equation, but what terms?

- To sum-up, no satisfactory solution has been still found to remove this instability without deteriorating the accuracy.

2 Global models with finite elements vertical discretisation.

In 2008 we were able to run with IFS (TL798L91) and ARPEGE (TL538c2.4L60), with a scheme which combined VFEs limited to the vertical integral operators of the non-linear terms, and finite differences anywhere else (derivatives of non-linear terms, and linear terms). Stable forecasts were produced with a predictor-corrector scheme. But we will see below that these encouraging results do not extend to models with a finer horizontal resolution.

No new finding were brought in 2009, 2010, 2011 and 2012, but ALADIN partners Jozef Vivoda and Petra Smoliková continued to work on this topics, and they presented new results in April 2013 (during an all staff ALADIN meeting at Reykjavik). One of these results could be sum-up as follows: redefining the finite-element basis (and maybe too the definition of η used in the VFE operators), the optional iterative algorithm inside the semi-implicit scheme (the one using `NITERHELM`) seems to converge quickly, which was not the case with the original VFE basis (note that this iterative Helmholtz SI solver is not the same thing as the –more expensive– so-called predictor-corrector implicit scheme discussed in all other parts of this paper). Jozef Vivoda and Petra Smoliková made code developments on top of CY36T1, which is now an old cycle; these developments must be updated on a more recent cycle (CY40) in order that they could be cleanly evaluated.

3 Limited area models with finite difference vertical discretisation.

3.1 Current operational version of AROME.

AROME has been put in operations at METEO-FRANCE in December 2008, with an horizontal resolution of 2.5 km. It currently runs with 60 levels, a timestep of 60 s, and a two-time level Semi-Lagrangian scheme (2TLSL) with SETTLS extrapolation. There is no predictor-corrector scheme switched on.

Some instabilities were observed in operational AROME during winter 2011-2012 in case of strong stratospheric jet. They were due to a too poor resolution of the stratopause area, which moreover was close to the model domain's top (the stratopause area actually exhibits very strong vertical gradients during some winter events, in extra-tropical areas). These instabilities have been removed in operation by bounding the magnitude of horizontal winds in coupling files (this ad hoc modification is a temporary one). For operational configurations, a special care should be taken to design levels with a correctly-resolved stratopause, or a model domain's top below the stratopause.

3.2 Finer resolution configurations.

Various tests have been done with finer horizontal and vertical resolutions. The future expected operational version of AROME will use a resolution of 1.3 km and a L90 set of levels. Model top has been lowered to 10 hPa (i.e. below the stratopause located near 1hPa) to avoid instabilities linked with strong top-stratospheric jet. It is expected to use a timestep of 45 s, with a "cheap" predictor-corrector scheme (option `LPC_CHEAP`).
Results of tests done with a 1.3 km version of AROME can be sum-up as follows:

- This configuration has been tested with various sets of 90 vertical levels (varying the lowest level between 1 and 10 m). Extensive tests on one case (Xynthia storm) have shown that the best compromise between numerical stability and physical results is to take a lowest level at 5 m.
- Various tests have been done with the L90 set of vertical levels with lowest level at 5 m. Runs are stable with a timestep of 45 s if a cheap predictor-corrector scheme is switched on. A significantly smaller timestep would be required if predictor-corrector scheme was switched off, since in this case, even runs with a timestep of 30 s are not always stable. The overcost of the `LPC_CHEAP` has been found to be quite small in AROME.
- Compared to the operational version of AROME (60 levels, 2.5 km), AROME-1.3km-L90 provides improvements on a subset of meteorological quantities like horizontal wind at 10 m, gusts, rainfall, size of convective cells. Impacts of increasing horizontal resolution is more important than those obtained when increasing vertical resolution.

Several cases have been tested so far in Meteo-France with an AROME model using a 0.5 km resolution grid.

- The first tests were performed to investigate a possible steep slope issue. With a sufficiently small timestep this configuration seems to be stable. The meteorological situations chosen were summer convective events, the rain fields seemed more realistic with better scores compared to the 2.5 km model.
- The Xynthia tempest situation was also run, with realistic orographic patterns, although on this situation the 2.5 km model already performed well.
- Another 0.5 km resolution configuration was designed in order to run on a 200x200 grid points domain around the Roissy-CDG airport. This model was set up as part of a SESAR 12.2.2 project in order to provide an input for a wake vortices prediction model.
- A PRACE project was submitted to run on the CURIE high-performance computer ($\simeq$ 80000 cores) with the goal to investigate a Mediterranean cyclogenesis as well as measuring the scalability of AROME on a few tens of thousands of computing cores. The first results show a good scalability up to 8000 cores.

For all these tests the 500m configuration is very similar to the current AROME 2.5 km configuration. The predictor-corrector scheme is activated with a time step between 10s and 20s depending on the orography of the domain. After some testing the shallow convection scheme was kept with its initial settings.

4 Limited area models with finite elements (VFE) vertical discretisation.

Some tests have been done with AROME-2.5km-L60 on one situation, simply changing finite difference into VFE in limited parts of the system (VFE are applied on vertical integrals, not on vertical derivatives, and finite difference vertical discretisation is kept for linear terms, to match constraint C1). Contrary to what was observed for a 10 km mesh-size global model, runs may be unstable. Tests have also been done with a timestep of 10 s instead of 60 s: that does not solve this instability (model blows up at the same range). Changing semi-implicit tunable constants does not solve anything.

Improvement could come from the work done by Jozef Vivoda and Petra Smoliková (see above).

5 Testing alternative dynamical cores.

Juan Simarro and Mariano Hortal (Spain) have started to evaluate an alternative NH dynamical core in HIRLAM: based on Z-vertical coordinate, with VFE, using Φ and w as NH prognostic variables. Work is still in progress, there are still issues. No code entered our LAM model. It seems that Juan Simarro and Mariano Hortal have now stopped to work on this topic, they would rather examine Jozef Vivoda and Petra Smoliková proposals.

ECMWF also plans to study alternative formulations of the governing equations themselves (anelastic and/or quasi-anelastic systems). In 2009 and 2010 Nils Wedi tried to find a quasi-anelastic formulation, but apparently he did not yet succeed to find an acceptable one. After that he switched to other actions. Christian Kuehnlein is now working on this topic, and future releases of this newsletter will provide more details about the work done.

There is now a brainstorming in Meteo-France about specifications of the dynamical cores which could be used after 2025. Some questions have been raised:

- High scalability on machines which might reach millions of processors with distributed memory.
- What type of vertical coordinate above steep slopes? It is not guaranteed that terrain-following vertical coordinates could still be used with slopes above 70%.
- Spectral representation could be abandoned for horizontal discretisation. Alternative grid-point discretisations must be examined.
- To sum-up, a lot of “possibles” exist, one must find the ones which will improve NWP and this is not an easy task.

ECMWF is in a similar prospective process as well (on a shorter term). Based on the widely accepted very small impact of using NH systems with grid-meshes of 10 km, the official deadline for an operational NH model at ECMWF has currently been delayed to the date when the grid-mesh will reach 5 km. The strategy for being able to have such an NH NWP system in operations at ECMWF at this date still lies on three avenues:

- improve the current version of IFS NH in order for it to be able to meet the requirements (efficiency, stability, quality of results).
- build a quasi-elastic version of the "current" dynamics (thus keeping SISL 2-TL spectral... techniques currently used). The problem of efficiently mixing a SI scheme with this governing equation system is not an easy one. This is because on top of the 3D Helmholtz equation of the SI scheme, there is a 3D Poisson equation for diagnosing pressure to be solved. This complication *inter alia* makes progresses difficult for time being, as reported above.
- build something rather new, probably in the family of anelastic (or quasi-elastic) systems, but not necessarily implemented with the latter list of techniques.

6 Conclusion.

There are still improvements in progress, when using finite differences vertical discretisation. These improvements focus on options without predictor-corrector scheme (how to use SETTLS extrapolation?).

About VFE discretication, Jozef Vivoda and Petra Smoliková proposals must be examined.

More precisions must be brought about long-term work to do for future NH dynamical cores. A sort of "working group" must be built, with regular meetings; and an answer must be quickly brought to "who does what?".

The proposal of trying to build an informal "sub-kilometric scale HARMONIE community" is still to be developed, in order to share experiences, to try to avoid dead-ends or redundant studies about problems. A mailing list should be build and other ideas are welcome.